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TECHNICAL TRANSLATION

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SOLAR RADIO PHENOMENA AND THEIR PHYSICAL INTERPRETATION

By J. F. Denisse

Translation of "Les Phénomènes radioélectriques solaires et leur interprétation physique." Presented at the 13th General Assembly of the Union Radio Scientifique Internationale in London, Sept. 12, 1960.

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SOLAR RADIO PHENOMENA AND THEIR PHYSICAL INTERPRETATION*

By J. F. Denisse

ABSTRACT

The various types of waves that can arise in the coronal plasma and the conditions for their escape beyond the corona are discussed.

The centimeter bursts of radiation and type IV bursts can be interpreted as synchrotron radiation of relativistic electrons. The bursts of type III and type II are most probably due to the excitation of oscillations of the coronal plasma by high energy particles; but whereas the particles responsible for type III seem to pass through the corona freely, those which radiate type II are probably trapped in a magneto-dynamic wave. Radio storms are probably also due to the excitation of oscillations of the coronal plasma by the particles initially ejected during an eruption, these particles remaining trapped for several days in the permanent magnetic configurations near the sun.

SOLAR RADIO PHENOMENA

Table I lists the most representative solar radio phenomena that can be considered as well identified, together with the main properties of these phenomena that will be used in the following discussion. All of these phenomena are more or less directly related to the chromospheric eruptions and constitute the essential phenomena of the sun's radio activity. There exist other equally well characterized, but rare, emissions; they are perhaps as interesting as the first but they constitute, in every respect, a small proportion of the solar activity, and we have not attempted to include them in this discussion.

Interpretations for most of these phenomena are still very uncertain, and this situation is due as much to the difficult and rudimentary character of radio observations as to the inadequacy of our theoretical knowledge of the properties of radiation from plasmas. Since we are unable to produce them, we cannot study suitable plasma models in the laboratory, that is, plasmas whose characteristic dimensions are large

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relative to the wave lengths radiated; on the other hand, theoretical studies are difficult and still very incomplete. Before discussing the interpretations of solar phenomena the situation will be discussed broadly from the theoretical point of view. There are two basic problems. One concerns the possibility of radiation from the coronal plasma; the other concerns the conditions of propagation of these emissions and the manner in which they can radiate outside the corona.

PLASMA RADIATION

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Figure 1 shows, for a representative case, the behavior of the dispersion curves of the four types of waves that can be propagated in a plasma. The ordinate is the square of the velocity index $\left(\frac{c}{V_e}\right)$. The abscissa is $\frac{\omega_0^2}{\omega^2}$, where ω_0 is the critical frequency of the plasma and ω is the wave frequency. In the high-frequency region which interests us, we distinguish between the ordinary modes (1) and the extraordinary modes (2), which can propagate outside the plasma, and the electronic modes (3) and ionic modes (4), which cease to exist outside the plasma. In a plasma in equilibrium these different waves are normally excited as a result of the agitation of the particles and correspond to the thermal radiation of the plasma, which explains the emissions from the main solar atmosphere and from the denser and hotter regions above the sun spots - the slowly varying components of the solar radiation. In particular, these thermal emissions of the corona at several million degrees are always of too low an intensity to explain the other types of solar emissions. To obtain a sufficiently intense radiation from the plasma, we must suppose that there exists superimposed on the thermal plasma, a group of particles having energy very much higher than the average. It can then happen that the velocity distribution function of the ensemble of the particles in the coronal milieu has a positive derivative for certain velocities greater than the mean velocity of agitation of the particles. This situation can occur, for example, when a group of particles of high energy, such as are produced at eruptions, is injected into the corona.

These high energy particles can augment the plasma radiation in several ways. First, they themselves can radiate like the other plasma particles because of their acceleration during collisions or in the magnetic fields of the solar atmosphere. Also, there can be thermal radiation corresponding, however, to the "temperature" of the group of energetic particles. These emissions are radiated in modes (1) and (2) and can propagate without hindrance to the exterior of the corona. Note that the emissions that arise from the magnetic acceleration, whether due to nonrelativistic particles (gyromagnetic emissions) or relativistic particles (sychrotron emissions), are for the most part radiated in the extraordinary mode (2).

These particles of velocities greater than the average can on the other hand excite in the plasma, by a process analogous to the Cerenkov effect, waves whose velocity of propagation in the plasma is less than the speed of light, that is, waves corresponding to modes (3) and (4) in regions where n^2 is greater than 1. The particles can excite the plasma individually as in the Cerenkov effect, or collectively, as in a fiber tube [tube à faisceau mêlés]. Practically, the waves excited in mode (3) have a frequency close to the critical frequency ω_0 of the plasma; the waves excited in mode (4) have a frequency close to the gyromagnetic frequency ω_L of the electrons; the former are analogous to the plasma oscillations, the latter to the waves which propagate the atmospheric whistlers.

Finally, Twiss has shown that these superthermal particles could also act statistically to amplify certain radiations produced in the midst of the thermal plasma by a stimulated-emission effect.

PROPAGATION IN THE CORONA

As has already been indicated, the gyromagnetic or sychrotron emissions, produced mainly in the extraordinary mode (2), can propagate outside the corona if the collisions, density gradients, and magnetic-field gradients are sufficiently weak and if the emissions are produced at altitudes above the critical altitudes. The representative point on figure 1 moves as indicated by the arrow when the density of the corona diminishes, finally attaining point I, which corresponds to electromagnetic waves in a vacuum. Only refraction effects could possibly prevent these emissions from reaching the earth, when they arise in regions rather distant from the center of the solar disk.

The situation is quite different for the waves excited on branches (3) or (4). When wave (3) also propagates in a medium of decreasing density, its speed becomes slower and slower, and its behavior in this case has not been studied; under the same conditions, an acoustic wave would produce a shock wave, but one can imagine that this electronic wave, in which the space charge plays an essential role, should be partially reflected and absorbed by the Landau effect as soon as its speed becomes too close to the mean speed of agitation of the electrons V_e.

In order to produce a radiation observable outside the corona, waves (3) or (4) would have to transfer part of their energy to modes (1) or (2) before being absorbed. The works on this subject have been summarized in the article by V. L. Ginzburg and V. V. Zheleznlakov (ref. 1). If we exclude the possibility of having within the corona abrupt variations in the plasma properties within a distance comparable to the wavelength, it seems that there are two possible transfer mechanisms. The first involves the diffusion of the plasma oscillations among the small-scale inhomogeneities of the coronal plasma: The transfer is from A to A' (fig. 1) in the ordinary mode. This mechanism is of interest in causing the waves of frequency ω and 2ω to appear as products of diffusion.

The second mechanism involves the coupling between the different modes introduced by the large scale variations of the density or of the magnetic field in the corona. The circles in figure 1 surround the regions where conditions for coupling appear à priori most favorable, that is, the regions where the phase velocities of the different modes are most nearly the same. We might note that in the presence of a magnetic field these coupling conditions are more favorable for a propagation direction close to the field direction. All these couplings result in radiation of the ordinary mode in a region A' where the phase velocity exceeds the velocity of light. The type (3) waves most likely to attain this region are those which progress, starting from point A in milieus of increasing density, as indicated by the arrow issuing from A (fig. 1). These conditions can be produced if the initial wave encounters a local density increase or if it propagates toward the interior of the corona. In this last case the ordinary wave formed will be reflected in the neighborhood of the critical altitude before radiating outside the corona.

All of these mechanisms occur near the altitude where the critical frequency is close to the wave frequency $\left(\omega \approx \omega_0\right)$ in the normal corona. Only meter waves or longer can propagate in these regions without considerable absorption; the shorter waves are strongly absorbed there. For this reason it seems impossible that the solar emissions of decimeter and centimeter waves might be due to excitation of modes (3) or (4). It is probably there that one should seek the origin of the considerable differences between the solar emissions of wave lengths greater than and less than about 50 cm.

INTERPRETATION OF SOLAR RADIO EMISSIONS

We shall now see to what extent the preceding considerations will provide interpretations for the different types of solar emissions. Practically, we have to choose between:

(a) Gyromagnetic emissions radiated in the extraordinary mode over a narrow bandwidth

(b) Synchrotron emissions radiated essentially in the extraordinary mode over a wide band and at an altitude practically independent of the plasma properties but above the critical altitude

(c) The emissions of the plasma itself, excited by the high-energy particles, in the neighborhood of the plasma frequency at $\omega \approx \omega_0$, or in the neighborhood of the gyromagnetic frequency at $\omega \approx \omega_L$.

These emissions are produced over a narrow band, and their transfer outside the corona should be in the ordinary mode.

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Centimeter bursts.- For the reasons that we have seen in the preceeding paragraphs, centimeter bursts are certainly due to the radiation from the energetic particles themselves; the synchrotron radiation must play the essential role for the "sudden-commencement" bursts. Certain "gradual rise and fall" bursts can be due to a local heating of the chromospheric plasma. Measurements of altitude and polarization will be necessary to confirm these hypotheses.

Type III bursts.- Type III bursts are certainly due to oscillations of type (3) excited in the corona by a sudden ejection of particles of very high energy; this is the interpretation first formulated by J. P. Wild (ref. 2). The fact that these bursts in general are not polarized indicates that these particles escape into regions without magnetic field. The existence of one and only one harmonic can be explained by Ginzburg's diffusion mechanism (ref. 1). It is also possible that the exciting particles are sufficiently numerous to produce a collective action and excite a wave of large amplitude whose higher order harmonics would be waves of low velocity, thus close to V_e and strongly absorbed by the Landau effect. The choice between these two hypotheses can be made by comparing the altitudes of emission of the fundamental and of the first harmonic. If the two are produced by diffusion, they must proceed from the same altitude, except for refraction effects; if not, the coupling phenomena must occur at very different altitudes, the harmonic proceeding from a much lower altitude than the fundamental. In case it should prove that the type III bursts are not observed directly, but following a reflection in the corona, one can note that the measured ejection speed would be less than the true speed, which could then be exactly equal to the speed of light. This would obviously be very important for the recognition of the nature of the exciting particles.

Type II bursts.- It has generally been proposed to explain type II bursts in a manner analogous to that which works for type III bursts, supposing the speeds of the exciting particles to be barely supersonic. We think that if such an excitation exists, it will produce essentially a wave of magnetodynamic type - that is, a pseudo-acoustic perturbation (wave 4', fig. 1) which propagates at type II speed, the high-frequency waves of low speed (waves 4 for $\omega \approx \omega_L$) being strongly absorbed. One can note in this connection that the sudden disappearances of protuberances, although sometimes supersonic, do not give rise to any radio emission.

It is possible, on the other hand, that in this magnetic wave there are trapped high energy particles entrained with it and accordingly capable of radiating all the types of waves that we have considered above: in particular, waves of type (3) at the plasma frequency and waves of type (4) at the gyromagnetic frequency, these two waves being finally radiated in the ordinary mode. These two emissions should be able to explain the doubling that the types II sometimes show; since this doubling is very distinct when it exists, it would be necessary to suppose that the magnetic field in the perturbation is not turbulent but remains essentially uniform with an intensity of the order of about ten gausses.

The remarks that we have made with regard to types III concerning the coupling problems are equally valid for the type II bursts which could then correspond to velocity perturbations appreciably greater than the measured velocities.

Type IV bursts.- The type IV burst, at least in its first phase, probably fits the interpretation proposed initially by A. Boischot and J. F. Denisse (ref. 4): It is the synchrotron emission of the high-energy electrons, produced at the moment of the eruption, which radiate into the coronal magnetic fields that arise above the active spots. Indeed the emissions of these bursts, which show no directionality, are not related to the critical frequency; furthermore, when they are observed toward the center of the disk, they tend to show a certain degree of extraordinary polarization. They should not be essentially different in nature from the centimeter bursts. It may be noted that their direct connection with the solar cosmic rays confirms this interpretation.

Radio storms and type V bursts.- In type V bursts the radio storms are circularly polarized in the ordinary sense with respect to the prevailing magnetic field of the associated spot. On the other hand, the directional and refractive effects that they show indicate that their emission source is connected with the critical frequency of the coronal plasma. They are, then, probably due to the excitation of modes (3) and (4) by fast particles. It happens rather frequently that a radio storm begins within the hour after the beginning of a great chromospheric eruption (if it is not located too far from the center of the disk) and continues for several days. It is, then, possible that the storms are also excited by the fast particles ejected during the eruption. It might be supposed that after their ejection these particles remain trapped somewhere in the neighborhood of the sun, like the solar cosmic rays, in some magnetic configuration probably associated with the coronal jets; diffusing slowly in these jets, they excite at each altitude waves of frequency close to the corresponding critical frequency.

Types V can possibly be explained in an analogous manner, with the exciting particles not being trapped in a magnetic field and diffusing very rapidly.

This interpretation of storms does not provide an explanation for the type I bursts that accompany them. It might nevertheless be observed that, in the meter-wave domain where the storms appear, the corona is a very good reflector and it is very probable that a part, at least, of the radiation that reaches us from the storms is observed by reflection from the corona; it is then possible to interpret the type I bursts as transient specular reflections involving a small bandwidth. Twiss has proposed to explain these bursts as emissions stimulated by the gyromagnetic emissions, but these emissions would have to have extraordinary polarization, contrary to observation.

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In view of the still fragmentary state of our actual knowledge, the hypotheses formulated can not pretend to be the true interpretation; they are discussed only in order better to direct interest and the orientation of future observations.

What is rather reassuringly evident from this discussion is that we can hope that the solar radio-astronomy observations, besides being interesting in themselves, are capable of contributing important data on certain fundamental properties of plasmas that our laboratories are not yet capable of reproducing and studying.

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TABLE I

Phenomena	Radiation	Polarization	Characteristic duration	Characteristics
Centimeter bursts	Continuum	Variable, often unpolarized	Minute	--------------------
Types III	Narrow band; sliding frequency, harmonic	Often unpolarized	Second	Ejection: $v \lessapprox c$; spectrum limited to meter waves
Types II	Narrow band; sliding frequency, harmonic	Often unpolarized	Minutes	Ejection: $v \sim \frac{c}{1000}$; spectrum limited to meter waves
Types IV (first phase)	Continuum; very broad band	Weak	Hour	Unpolarized at the edge; weak extra-ordinary polarization at the center
Type V	Continuum	?	Minute	Spectrum limited to meter waves
Radio storms	Continuum + types I	Strong, circular, ordinary	Days	Spectrum limited to meter waves

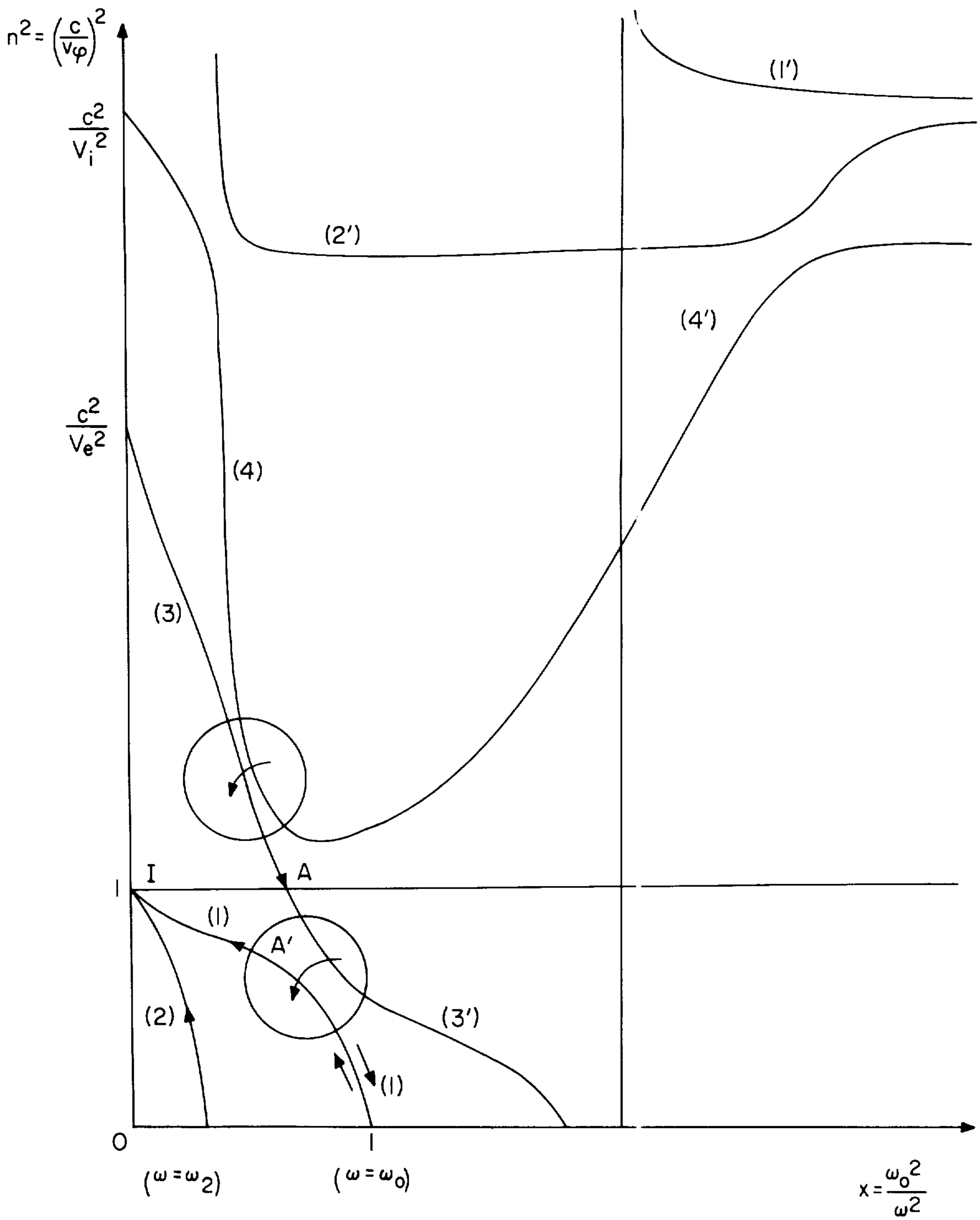

Figure 1.

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